Opportunistic Spectrum Usage: Bounds and a Multi-band CSMA/CA Protocol

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Commonly Held Vision

- High throughput
- High availability
- Economic viability

Killer app is the network itself

- Fast cheap access in public places, homes
- Like utilities (only mobile)

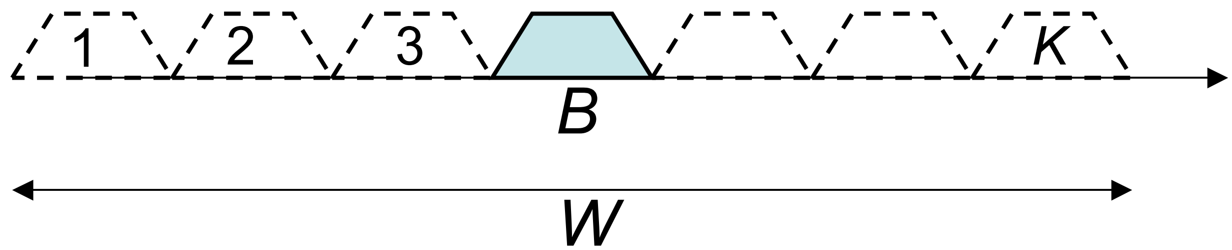
Common “Complaints”

- Not enough spectrum
  - Small amount of commercial spectrum $\Rightarrow$low data rates
  - True, but scarcity a by-product of an antiquated FCC
- A large fraction of allocated spectrum is unused
  - New opportunities, new FCC policies
  - Wireless LAN has 80+ MHz, we use only ~20 MHz
- Wideband systems expensive to build
  - True a decade ago
  - Ultra-wideband radios, cognizant radios,…
- Claims
  - Lots of spectrum available, we just don’t use it well
  - Opportunities to exploit large amounts of spectrum cheaply

Outline

- Opportunistic use of spectrum
  - Capacity-measurement tradeoff
  - Guidelines on channelization
- A protocol implementation
  - MOAR protocol
  - Optimal skipping rule
  - Simulation results
- Conclusions

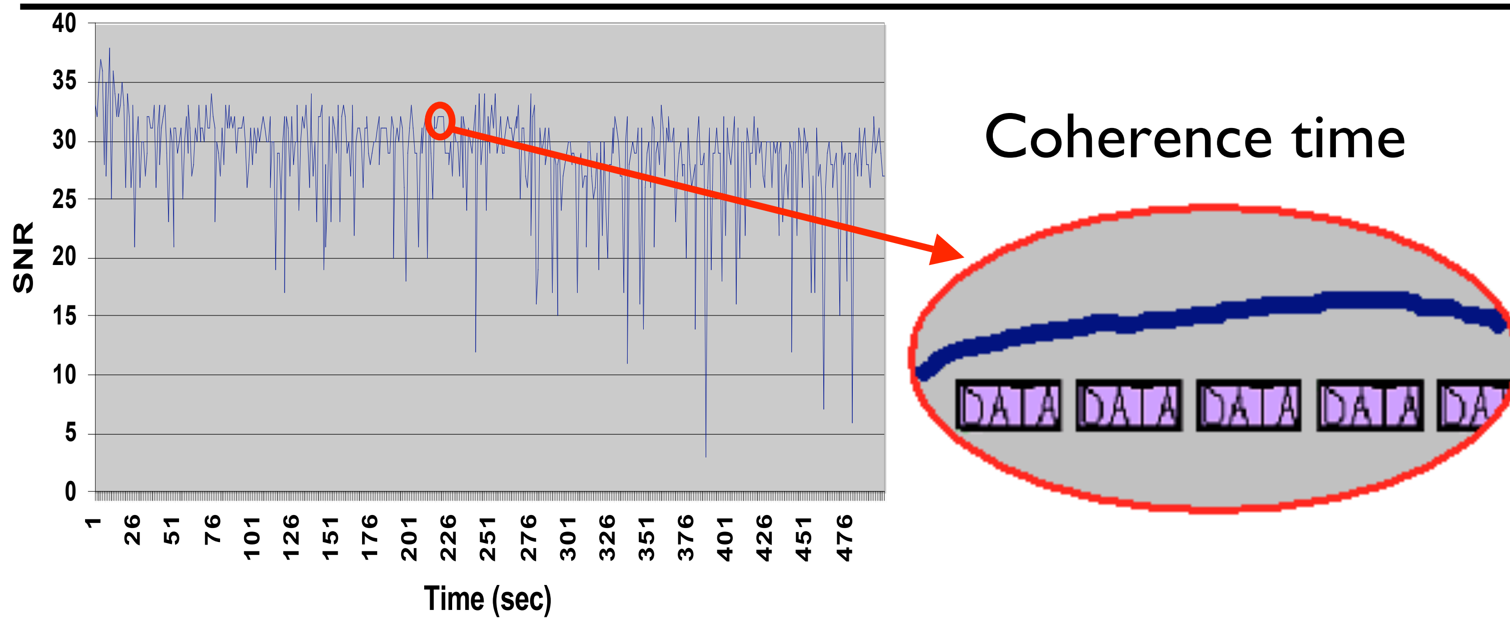
Basic Setup



- Large bandwidth, *W* Hz
- Divided into *K* bands of *B* Hz each

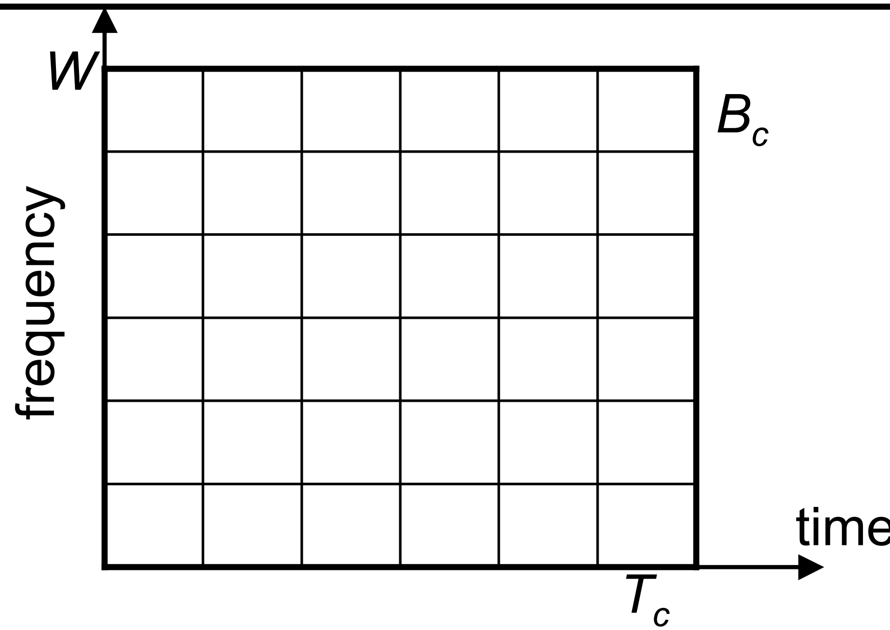
- Examples
  - IEEE 802.11b : 3 bands
  - IEEE 802.11a : 8 bands

Facts About Wireless



- Coherence time
  - Time for which channel gain is almost constant
- Coherence bandwidth
  - Bandwidth over which channel gain is almost constant

Time-frequency Partition



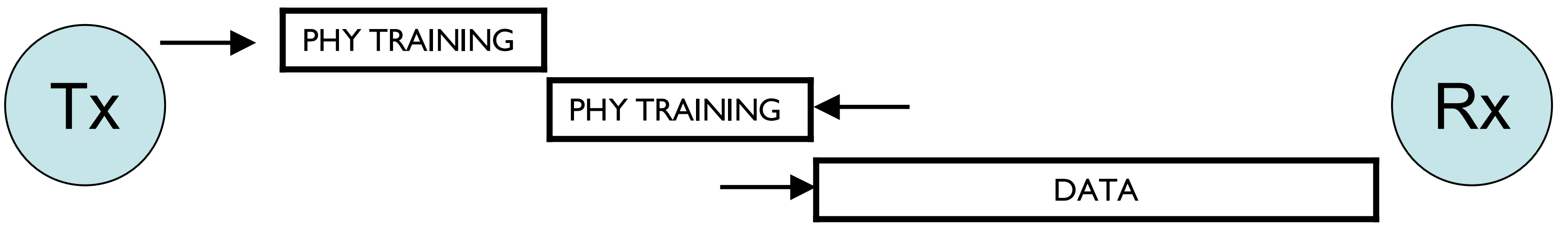
- Partition the time-frequency plane into (T_c, B_c) tiles
- Each tile characterized by one complex gain
  - $Y_i = H_i X_i + noise$
  - $SNR_i = |H_i|^2$ such that $E(SNR_i) = \mathbf{SNR}$
- Channel gain H_i unknown to both transmitter and receiver

Obtaining Channel Knowledge

- Transmitters and receivers do not know the channel
- Time-variation $\Rightarrow$ periodic measurements required

- Channel measurement consumes resources
  – One-way : τ fraction of total time

Obtaining Channel Knowledge



- Transmitters and receivers do not know the channel
- Time-variation $\Rightarrow$ periodic measurements required

- Channel measurement consumes resources
  - One-way : τ fraction of total time
  - Two-way : 2τ fraction of total time

Genie-aided Capacity

- Assume all *K* band channels are known perfectly
- Capacity-achieving method chooses the best band

$$
\begin{aligned}
R^*(K) &= B\mathbb{E}\left[\log\left(1 + \max_{i=1,\ldots,K} SNR_i\right)\right] \\
&\sim B\log\left(\overline{\mathsf{SNR}}\log K\right)
\end{aligned}
$$

- Gains from opportunism
  - Linear in per-band bandwidth, *B*
  - Doubly logarithmic growth in number of bands, *K*
  - Large number of bands not useful, large bandwidth is

Single-rate Transmission

- Transmitter makes no attempt to learn the channel
  - Chooses a fixed rate *R*
  - Only receiver measures the channel with overhead τ
  - When *current* channel capacity less than *R*, the packet is lost

- Net throughput

$$R_s = \frac{1}{1+\tau} R \mathrm{Prob}\left[B \log\left(1 + \mathsf{SNR}_i\right) > R\right]$$

- Throughput is independent of # of bands, *K*

Measurement-based Band Selection

- Measure K_m bands before sending data
  - Overhead = $K_m\,(2\tau)$ fraction of total time
  - Grows linearly with number of measured bands
  - Assume perfect estimates

- Choose the best possible band

$$\begin{aligned} R_m(K_m) &= \frac{1}{1+2\tau K_m} B\mathbb{E}\left[\log\left(1+\max_{i=1,\ldots,K} SNR_i\right)\right] \\ &= \frac{1}{1+2\tau K_m} R^*(K_m) \end{aligned}$$

Optimal Number of Bands

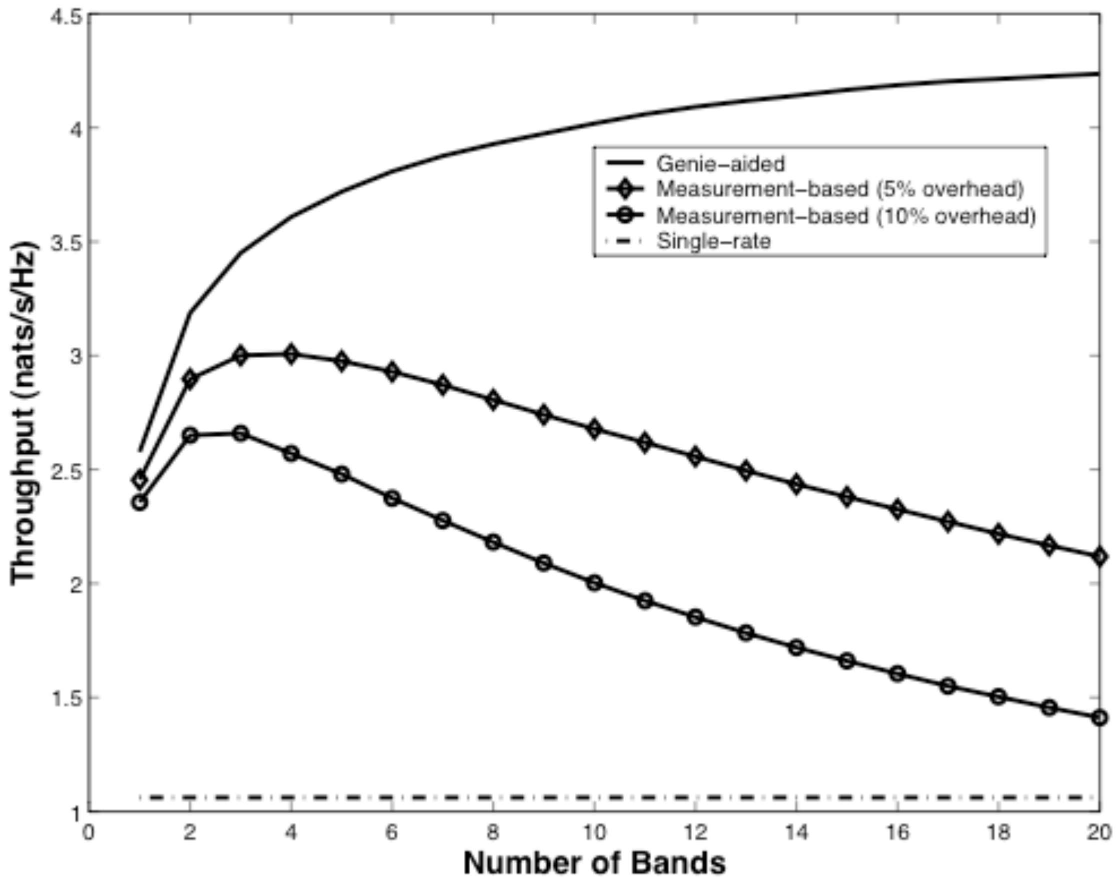
$$R_m(K_m) = \frac{1}{1+2\tau K_m} B\mathbb{E}\left[\log\left(1 + \max_{i=1,\ldots,K} SNR_i\right)\right]$$
$$= \frac{1}{1+2\tau K_m} R^*(K_m)$$

- $R^*(K_m)$ grows doubly-logarithmic in K_m
- Overhead grows linearly in K_m
- As $K_m \uparrow$, $R_m(K_m) \to 0$

- More opportunism $\neq$ more throughput
- In fact, there is an optimal K^*_m

Numerical Example

- $E(SNR_i)$=10dB
- τ = 5%, 10%
- K^*_m=3, 2



- Smaller $\tau \Rightarrow$ bigger K^*_m
- Channel-based adaptation useful

More Bands or More Bandwidth ?

- Given bandwidth $W=KB$, how should we divide it
  - More bands, K ? *Or*
  - More bandwidth/band, B ?

- *Proposition: For both genie-aided and measurement-based systems, $B=W$ is throughput optimal.*

- If you can, do not divide into smaller bands
  - Cost could be a factor
  - Unclear if network-wide optimal

Recap

- The short time-scale opportunism has its limits
  - Measurement overhead Vs. the benefit derived from it
  - Optimal strategy is to check a small number of bands
- Analogy for students
  - Many great research topics, but jump too often and the overhead will kill you

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Goals for Protocol Design

- Context is IEEE 802.11a/b/g
  - Coherence bandwidth is 1-3 MHz
  - Multiple bands (11+) which are >5MHz
  - Some bands completely orthogonal (3 to 8)
  - Both temporal and spectral opportunism available
- Two main parts
  - Accessing the floor
  - Measuring and choosing the right band

MOAR Protocol Sketch

- Accessing the floor
  - Assign a home band for all the nodes
  - Everyone contends in the home band using IEEE 802.11 DCF
  - Use 4-way handshake (RTS/CTS/DATA/ACK)
- Measuring channel quality in different bands
  - RTS/CTS used for channel measurement
  - If band SNR < threshold, skip to a new band (piggybacked in CTS)
  - Continue skipping till you beneficial
- Multi-band Opportunistic Auto-rate (MOAR)
  - Stopping rule
  - Adaptation for each node

Stopping Rule

- Nodes make a run-time decision on how many bands to measure
  - The number different for each node
  - Number varies with time due to node mobility
- Pose it as stopping rule problem
  - *Marriage problem*: How many people you meet before making THE decision ?
- In our problem
  - Recall is possible, but need to ensure no one else has the band after we left
  - Conservative approach: stopping rule *without* recall

Optimal Stopping Rule

- Optimal rule is threshold based
  - If $Rate_n < V^*$, continue; if $Rate_n > V^*$ stop
  - $N^* = \min\{n \geq 1 : Rate_n \geq V^*\}$

- $V^* = E \max(Rate_1, V^*) - c$

$$\int_{V^*}^{\infty} (Rate - V^*) dF(Rate) = c$$

  - *F(Rate)* represents the Rate distribution
  - c is cost of measurement

- *F*(*Rate*) depends
  - Average SNR ⇔ Fading parameters K-factor, distance,…

Using Time Coherence

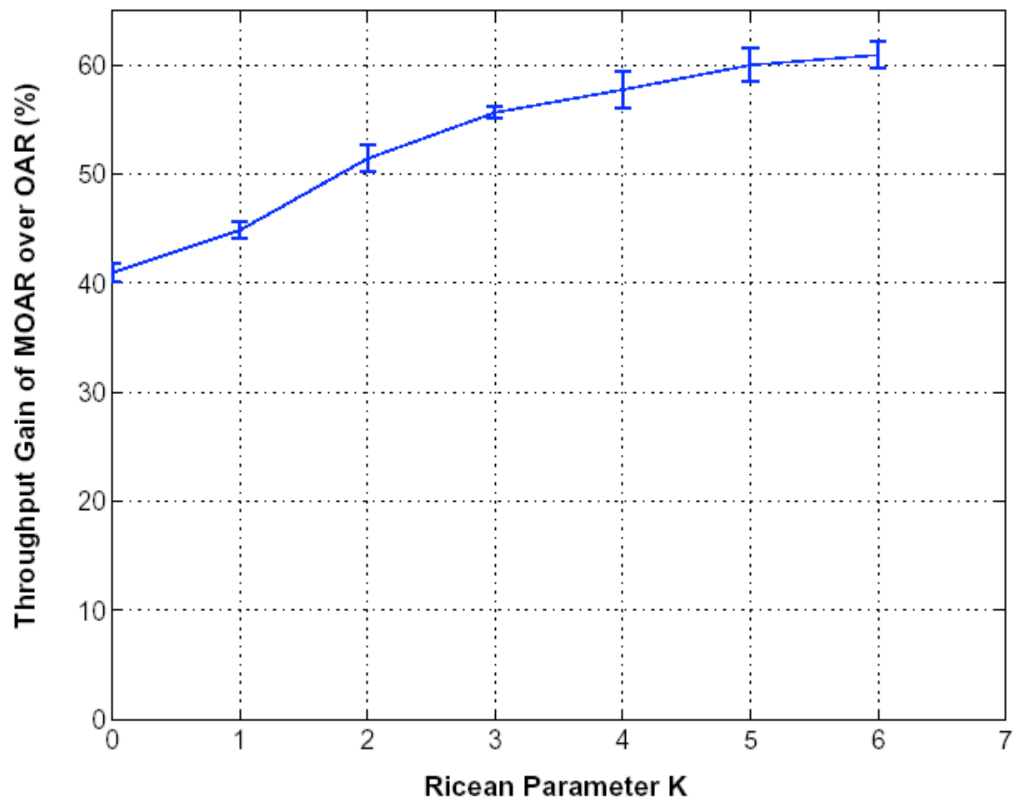
- To exploit time coherence (OAR)
  - Send multiple back to back packets
  - Number of packets = (Current rate)/(Base rate)
  - Higher rates imply higher number of packets

- OAR ensures
  - Same time-fairness as single-rate IEEE 802.11
  - Opportunistically reduces contention
  - Gets large gains over IEEE 802.11

- Whenever skipping stops
  - Send number of packets based on OAR

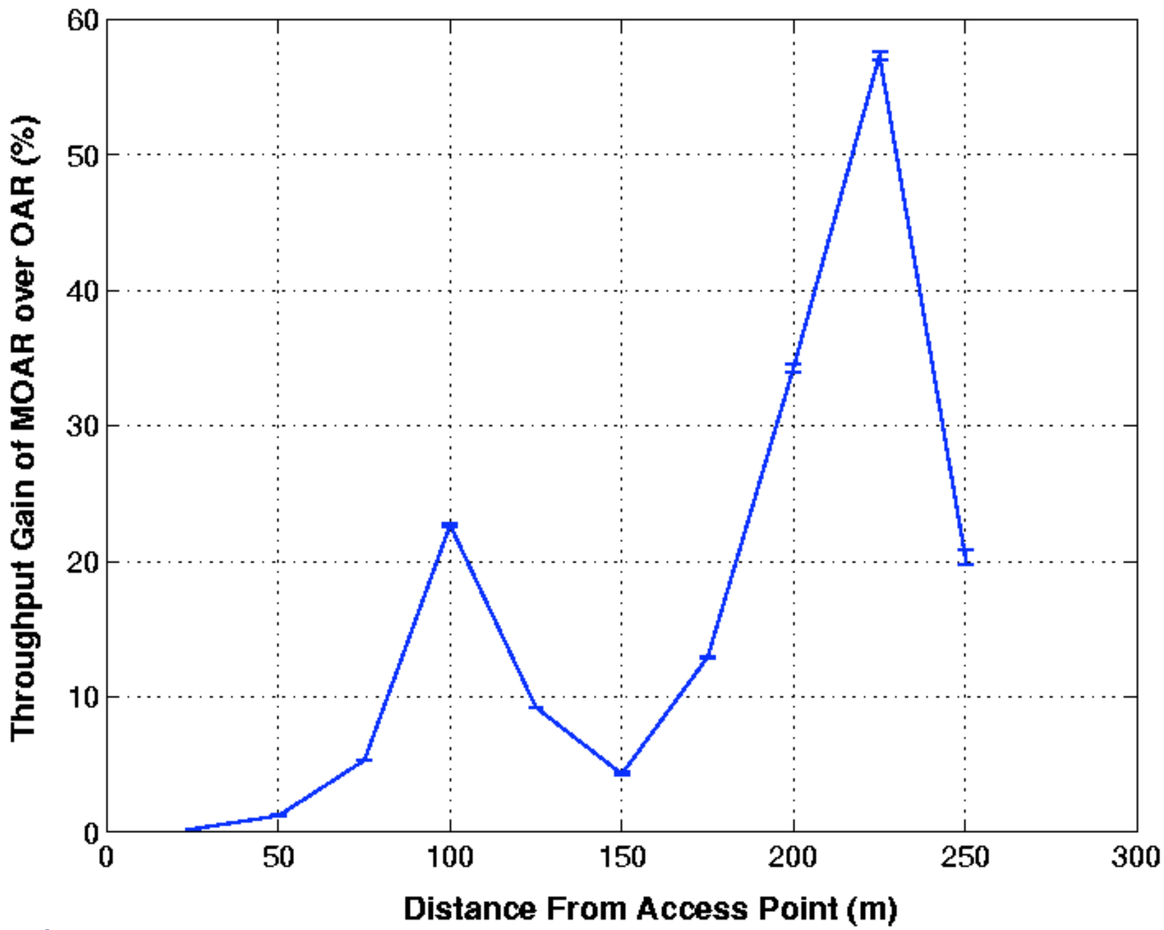
MOAR Throughput Gains

- Temporal opportunism - OAR
- Temporal + spectral opportunism - MOAR
- Gains of 40%-60% increasing with Ricean K-factor and SNR variance



Effect of Node Distance

- Greatest help when far away
- Non-monotonic due to rate-SNR thresholds



Conclusions

- Case for spectral reuse
  - Many services sporadically used
  - Reuse spectrum when available
- Reusing requires finding availablility
  - Interference, channel quality
  - Fundamental tradeoff between *discovering* and *using* opportunism
- Real gains available, nonetheless
  - Practical protocol in 802.11 framework
  - Many-fold gain over current standards